Painting injection to the Fermilab Main Injector

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Painting injection is required to realize uniform density distributions of the beam in the transverse plane for space charge effect reduction. This preserves emittance at injection.

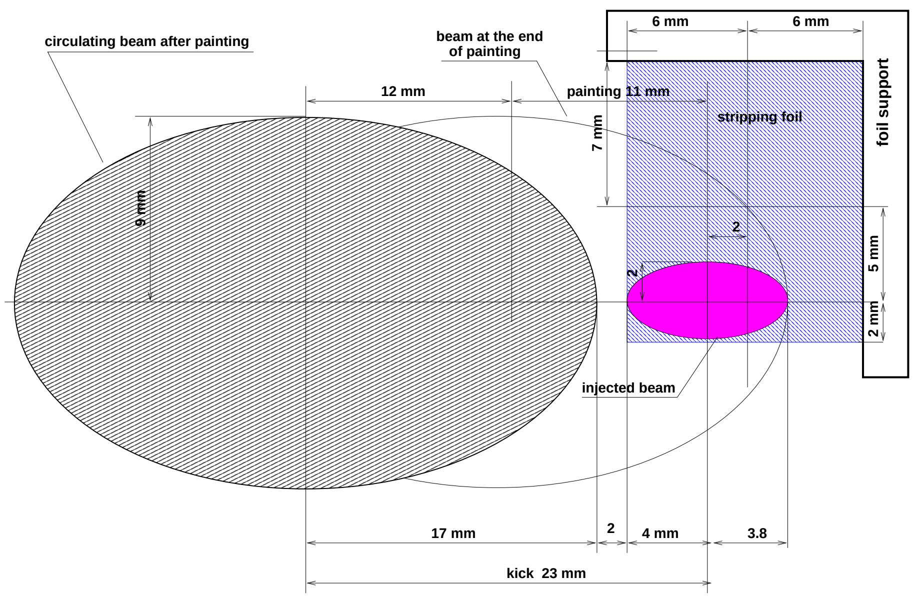


Figure 1: Injected and circulating beam location in the foil at painting.

Injection of 8 GeV H^- beam into the MI-30 straight section of the Fermilab Main Injector [1] is simulated. Painting injection [2] is performed by using two sets of fast horizontal and vertical magnets (kickers). The proton orbit is moved in the horizontal plane at the beginning of injection by 23 mm to the thin graphite stripping foil to accept the first portion of protons generated by H^- in the foil (Fig. 1). Three 1.5 m long kicker magnets are used to produce orbit displacement (Fig. 2). The maximum field of the kicker magnets is 0.41 kG. The horizontal kick at the beginning of beam painting is shown in Fig. 3. Gradual reduction of kicker strength permits "painting" the injected beam across the accelerator aperture with the required emittance. Vertical kicker magnets located in the injection line (not shown here) provide injected beam angle sweeping during injection time, starting from maximum at the beginning of injection and going to zero at the end of painting process. Horizontal and vertical kickers produce particle betatron amplitude variation during injection. This results in a uniform distribution of the circulating beam after painting. Painting starts from the central region of phase space in the horizontal plane and from the border of it in the vertical plane, and goes to the border of the beam in the horizontal plane and to to the center in the vertical plane. This produces a so called "uncorrelated beam" with elliptical cross section, thereby eliminating particles that have maximum amplitudes in both planes simultaneously.

A 9 m long septum-magnet located upstream of the foil (Fig 3) is used to separate the proton and H^- beams at the quadrupole upstream of the foil by 204 mm with septum-magnet field of 0.8 kG, and by 167 mm with septum-magnet field of 0.6 kG. This allows the H^- beam to pass outside the quadrupole body. The beam dump located behind the stripping foil is used for H^o interception. Injection kickers cause negligible perturbation of the β functions and dispersion at injection (Fig. 3). Horizontal dispersion in the foil at injection produced by the bump is equal to 0.023 m.

Multi-turn particle tracking through the accelerator is done with the STRUCT [3] code. A stripping foil made of 300 μg/cm^2 (1.5 μm) thick graphite has the shape of so-called corner foil, where two edges of the square foil are supported and the other two edges are free. The foil size is 1.2 cm $\times$ 1.4 cm.

The dependence of kicker-magnets strength on time is chosen to get uniform distribution of the beam after painting both in horizontal and vertical planes. An optimal waveform of bump-magnets [4] was simulated in the STRUCT code as presented below:

- in the horizontal plane

$$B = B_o \left[0.5217 + 0.4783 \left(1 - \sqrt{\frac{2\,N}{270} - \left(\frac{N}{270}\right)^2} \right) \right] \qquad N < 270 \qquad (1)$$

$$B = B_o \left[0.5217 - \frac{N-270}{11.5} \right] \qquad\qquad N > 270 \qquad (2)$$

- in the vertical plane

$$Y' = Y_o' \sqrt{2\frac{270-N}{270} - \left(\frac{270-N}{270}\right)^2} \qquad\qquad Y_o' = 0.6789\, mrad \qquad (3)$$

Here N is the turn number from beginning of painting.

The normalized emittance of injected beam at 95$\%$ is equal to 2 mm·mrad. The circulating beam emittance after painting is 40 mm·mrad, and accumulated intensity of the circulating beam is $1.5 \cdot 10^{14}$ protons. Painting lasts during 270 turns, and after painting the circulating beam moves out of the foil during 6 turns. In the simulations the horizontal bump amplitude at the foil is 23 mm = 11 mm (painting) + 12 mm (removing from the foil) (Fig. 1). Vertical angle variation is 0.6789 mrad. The transverse plane of the beam in the foil at turn number 10, 270, and 276 from the beginning of beam painting are presented in Fig. 5.

Horizontal kicker-magnet strength and vertical angle of the beam in the foil during injection are presented in the top of Fig. 6. Particle transverse population and particle density distribution after painting at the foil location are shown in the middle and at the bottom of Fig. 6.

Average number of hits upon the stripping foil for each particle is equal to 21.4. This effects pretty high level of nuclear interactions and multiple Coulomb scattering in the foil at injection, and because of this causes 0.074% of particle loss at injection. The reduction of painting injection duration to $90\ \mu m$ permits to decrease the average number of hits upon the stripping foil to 6.3, that reduces foil heating and beam loss at injection.

The circulating protons pass several times through the foil and some of them can be lost because of scattering in the foil. Multiple Coulomb scattering is small because of small foil thickness. Particle energy loss in the foil at one pass is $4{\cdot}10^{-8}$ of initial energy. The rate of nuclear interactions in the foil during the total process is $6.6{\cdot}10^{-5}$ of injected intensity for 270-turn injection and $2.0{\cdot}10^{-5}$ for 90-turn injection. The emittance of the circulating beam in the horizontal plane is small in the beginning of painting and it gradually reaches maximum only at the end of painting. Therefore particle horizontal amplitude, in average, is sufficiently less compared to the accelerator aperture. Particles can be lost only during the first few turns after injection, and only in the region of injection kick maximum and MI Lambertson magnets where the beam is close to accelerator aperture. At every next turn after particles are injected, they move away in horizontal plane from the aperture restriction at the injection region because of reduction of painting kick amplitude. But in the vertical plane the beam is close to the Lambertson magnet septa during the total cycle of injection, because painting starts from large vertical amplitudes. Simulations shown that the rate of particle loss in the accelerator at interaction with foil is as low as $7.4 \cdot 10^{-4}$ of the injected intensity for 270-turn and factor of three less for 90-turn injection. Beam loss distribution at injection with graphite foil thickness of $1\ \mu m$ for 90-turn injection with normal size of injected beam is shown in Fig. 14.

1 Conclusions

Painting injection system, which consists of two sets of horizontal and vertical kicker magnets, permits to realize quasi-uniform density distribution of the circulating beam required for the beam space charge effect reduction and emittance preservation at injection.

The calculated stripping efficiency is $??.?\%$, and estimated yield of excited states H$^o(n)$ atoms with $n \geq 5$ is equal to $0.0??\%$. These atoms become a beam halo.

The temperature buildup during injection pulse and steady state temperature of the foil are calculated from analytical distribution of proton hits using ANSYS code. An instant temperature buildup, calculated with contributions of multiple collisions, ionization loss from protons and electrons accompanied stripping process, is about 2400K.

With only emission as a cooling mechanism the foil temperature reaches a steady state of $\sim$ 3500K after 2 cycles of injection.

References

[1] Main Injector Technical Design Handbook, Fermilab, November 1995

[2] “The proton driver design study”, Fermilab-TM-2136, December 2000.

[3] I. Baishev, A. Drozhdin, and N. Mokhov, ‘STRUCT Program User’s Reference Manual’, SSCL–MAN–0034 (1994), http://www-ap.fnal.gov/~drozhdin/

[4] ’JHF Accelerator Design Study Report’, KEK Report 97-16, JHF-97-10, March 1998, p3-67 - 3-71..

[5] ANSYS v5.5 Manual, 1994.

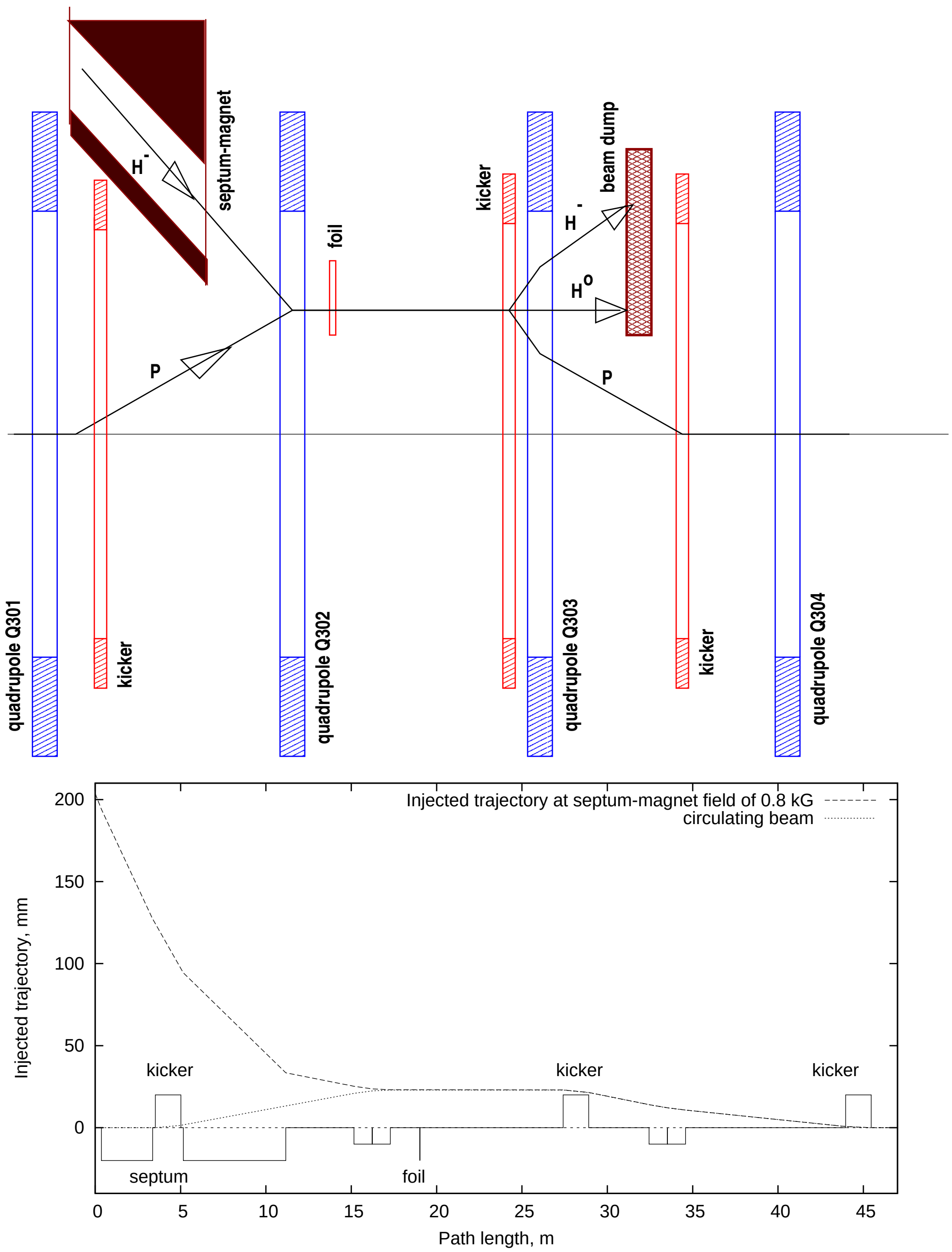


Figure 2: Painting injection scheme (top) and beam trajectory (bottom).

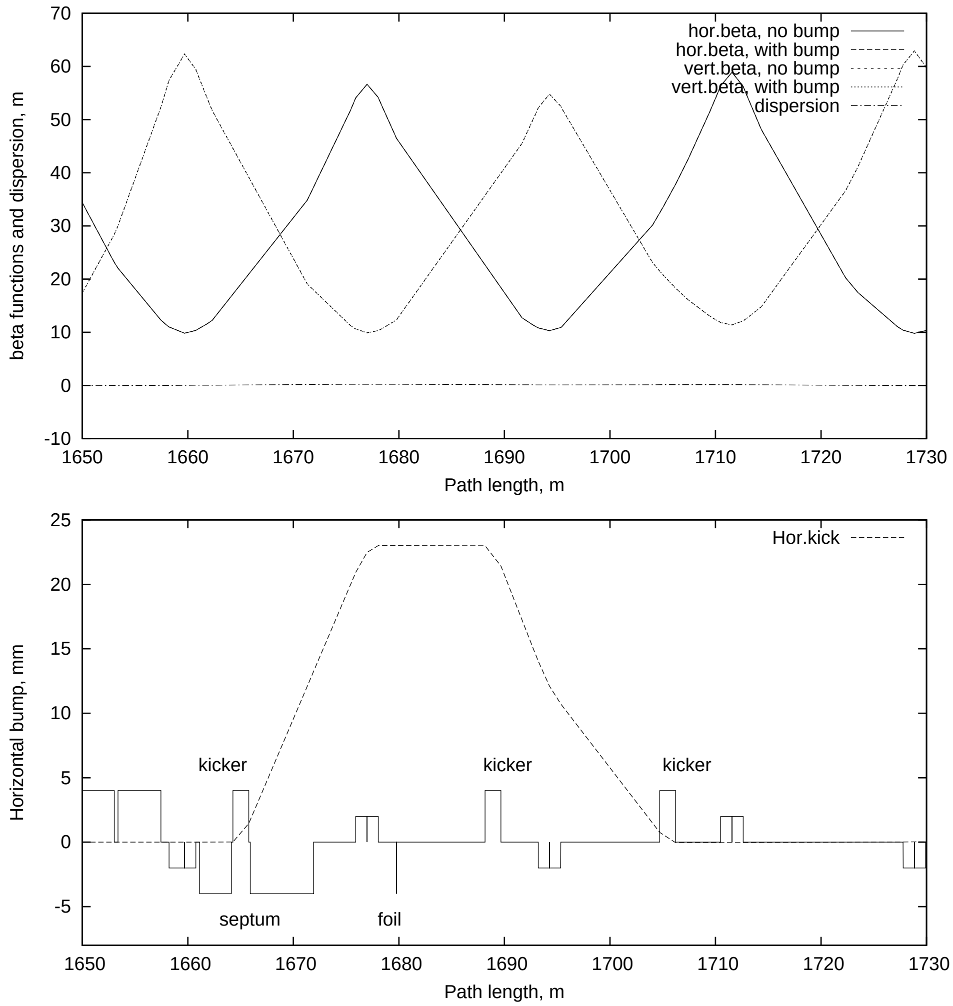


Figure 3: Beta functions and dispersion (top) and horizontal bump at painting injection (bottom).

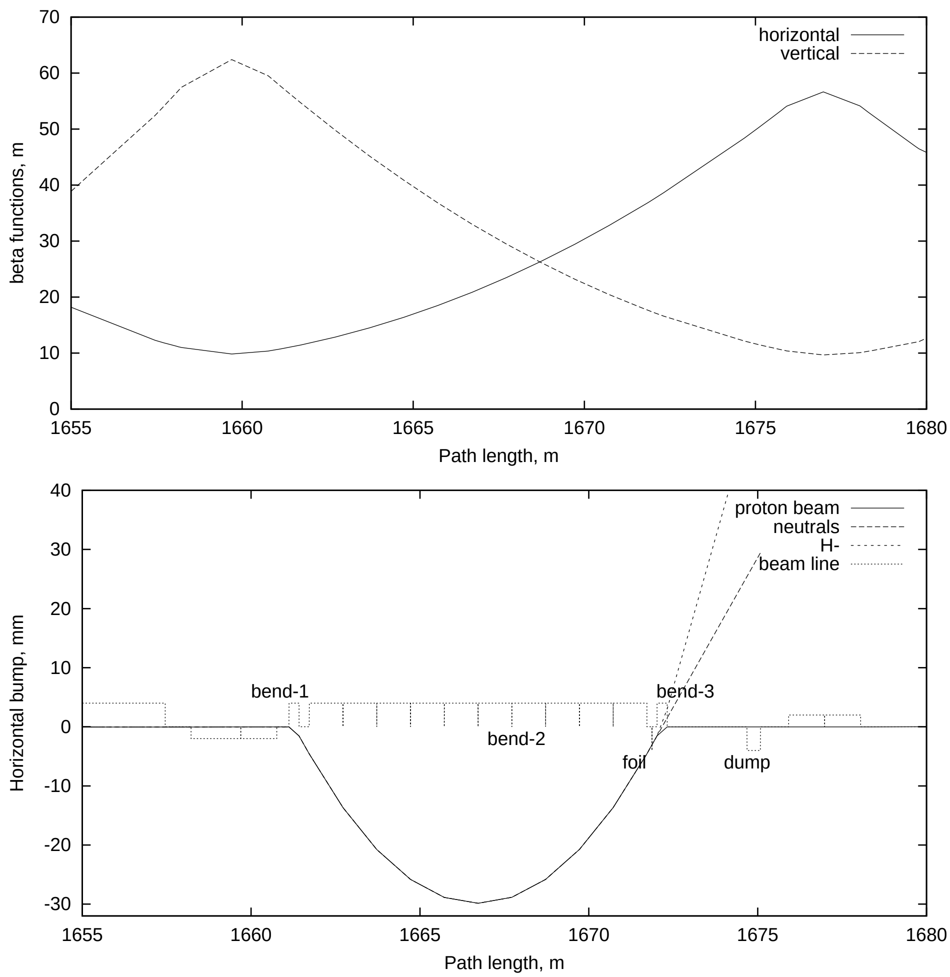


Figure 4: Beta functions (top) and horizontal bump (bottom) for optional scheme of painting injection.

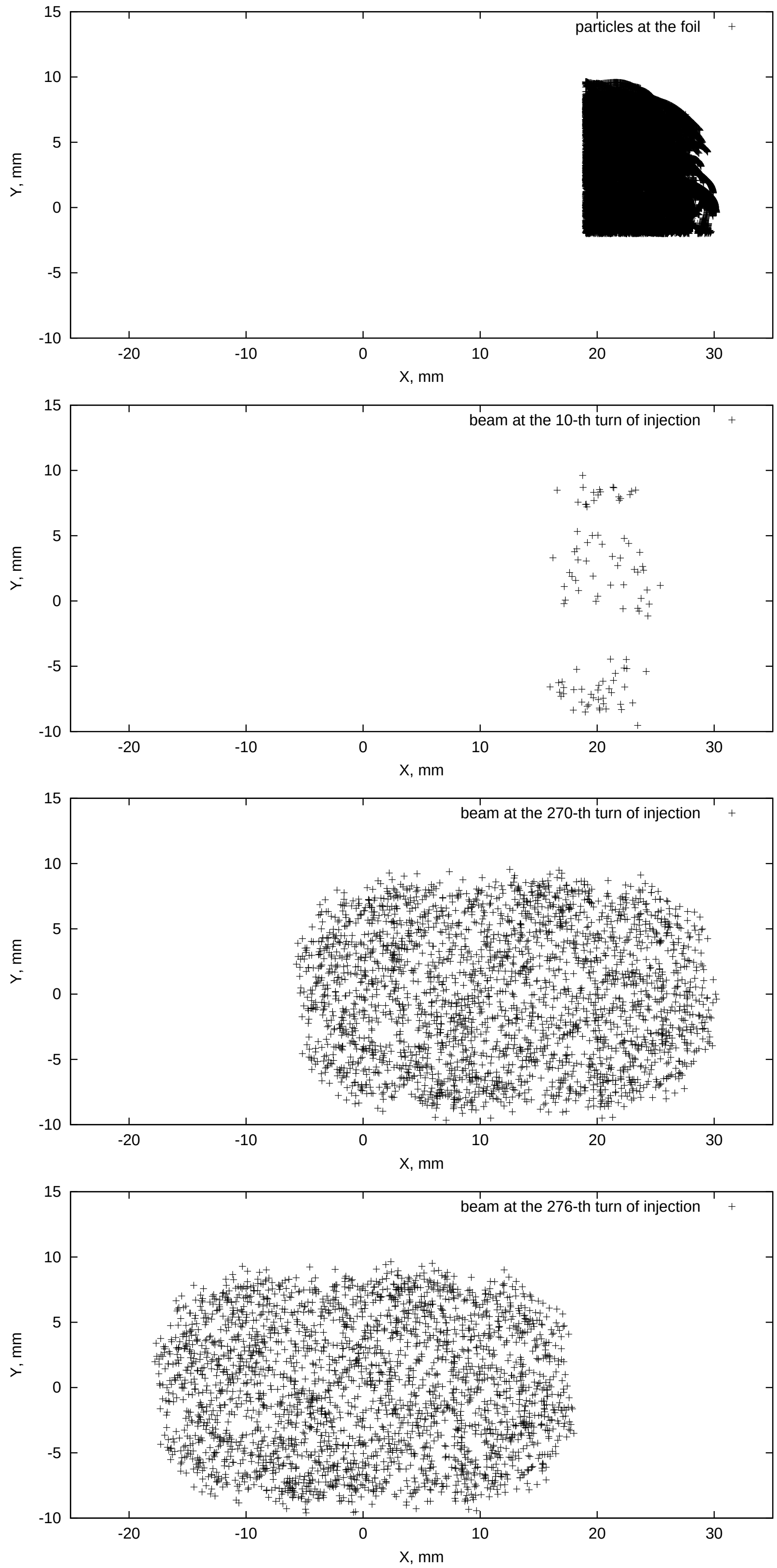


Figure 5: Particles passed through the foil during the total cycle of injection (top), circulating beam after 10 turn of injection (second line), after 270 turn (third line), after beam removal from the foil at 277 turn (bottom). Average number of each particle hits on the foil is 86707/4050=21.4. Betatron tunes are $\nu_x = 26.43, \quad \nu_y = 25.42$. Graphite foil thickness is $1\ \mu m$. Gaussian distribution of injected beam (with cut to 3 σ). Painting to 11 mm in horizontal plane.

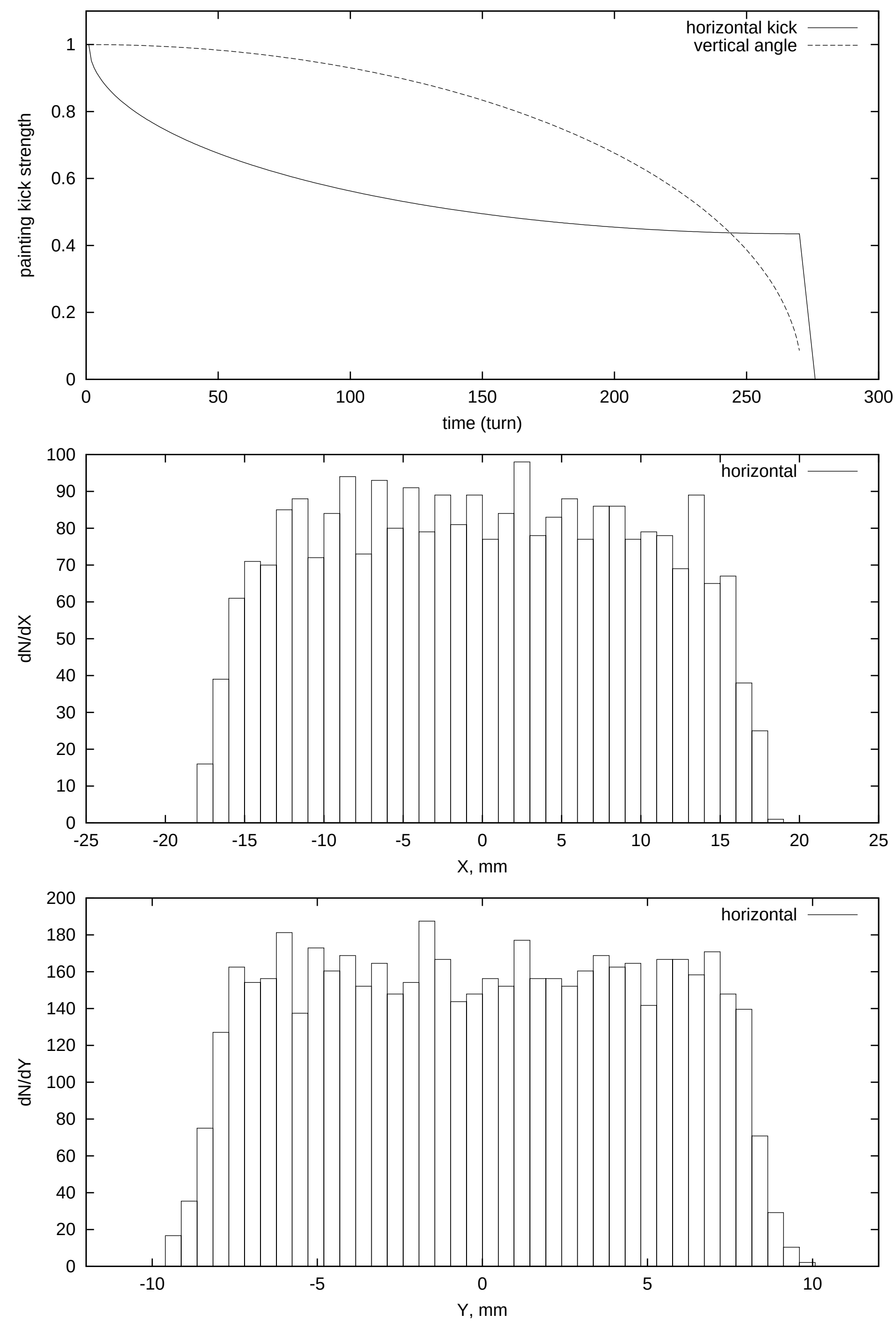


Figure 6: Horizontal kicker strength and vertical angle of the injected beam at the foil (top), circulating beam horizontal (middle) and vertical (bottom) density distribution after injection (276 turn). Graphite foil thickness is $1\ \mu m$. Gaussian distribution of injected beam (with cut to 3 σ). Painting to 11 mm in horizontal plane.

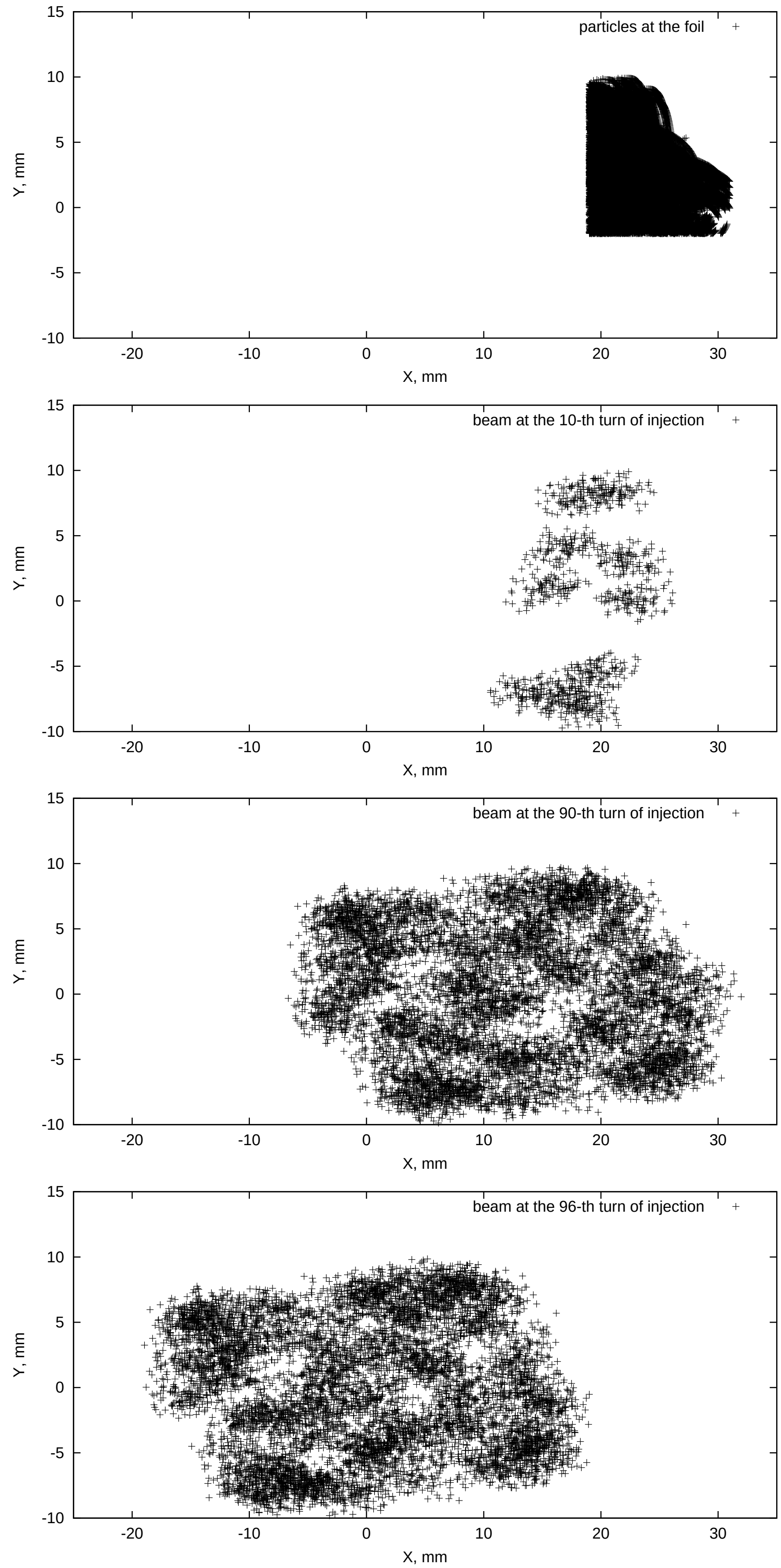
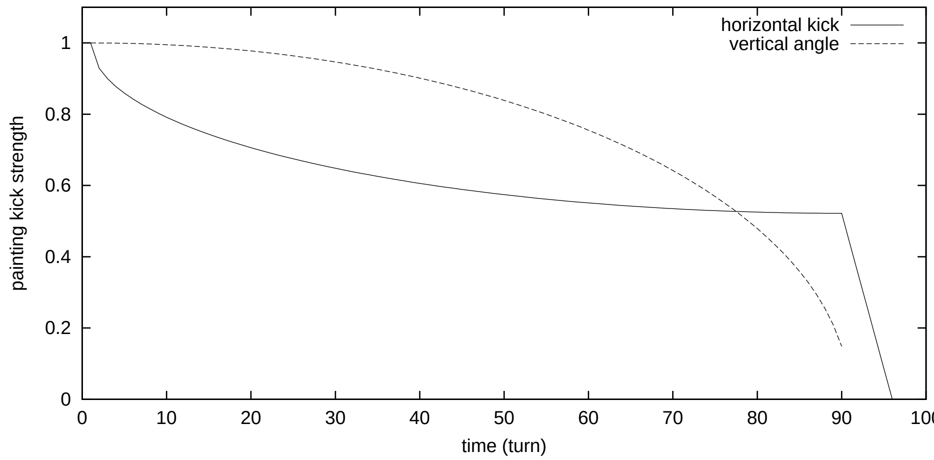
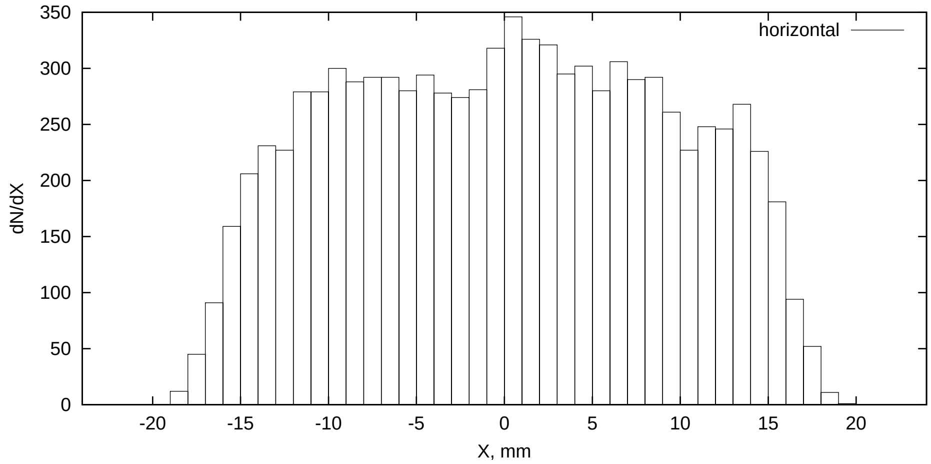


Figure 7: Particles passed through the foil during the total cycle of injection (top), circulating beam after 10 turn of injection (second line), after 90 turn (third line), after beam removal from the foil at 97 turn (bottom). Average number of each particle hits on the foil is 56659/9000=6.3. Betatron tunes are $\nu_x = 26.43, \quad \nu_y = 25.42$. Graphite foil thickness is $1\ \mu m$. Gaussian distribution of injected beam (with cut to 3 σ). Painting to 11 mm in horizontal plane.





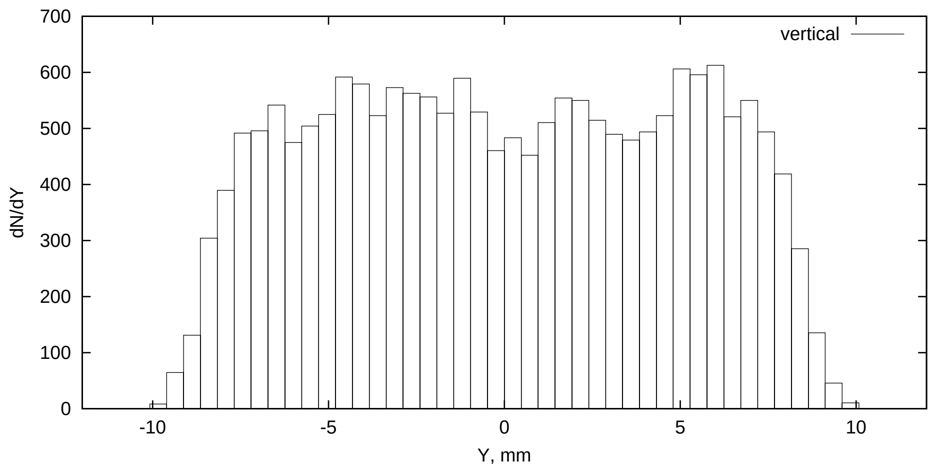


Figure 8: Horizontal kicker strength and vertical angle of the injected beam at the foil (top), circulating beam horizontal (middle) and vertical (bottom) density distribution after injection (96 turn). Graphite foil thickness is $1\ \mu m$. Gaussian distribution of injected beam (with cut to 3 σ). Painting to 11 mm in horizontal plane.

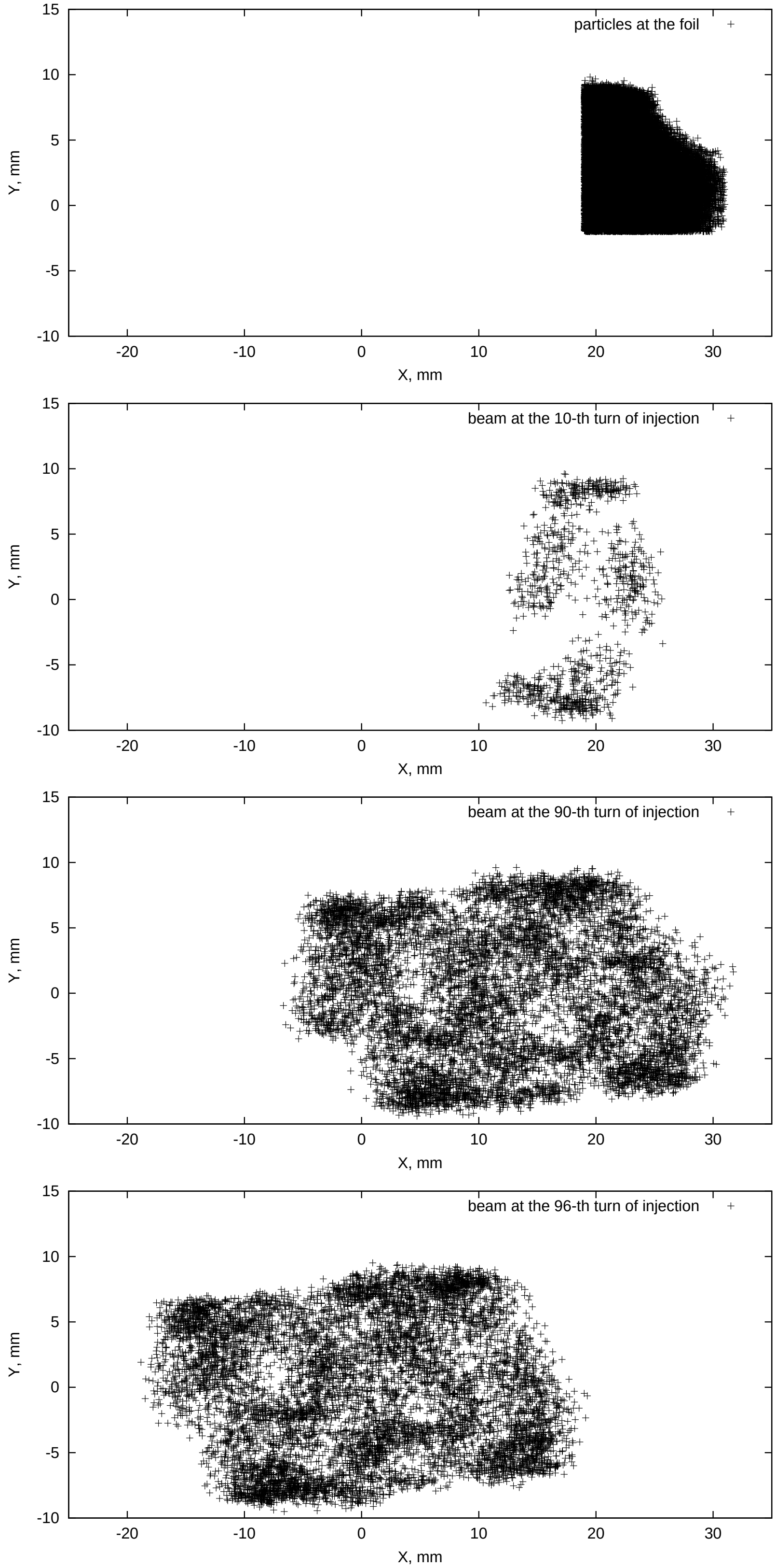


Figure 9: Particles passed through the foil during the total cycle of injection (top), circulating beam after 10 turn of injection (second line), after 90 turn (third line), after beam removal from the foil at 97 turn (bottom). Average number of each particle hits on the foil is 55629/9000=6.2. Betatron tunes are $\nu_x = 26.43, \quad \nu_y = 25.42$. Graphite foil thickness is $1\ \mu m$. Gaussian distribution of injected beam (with cut to 3 σ). Painting to 11 mm in horizontal plane. Vertical size of injected beam is increased by a factor of 2 (no emittance increase).

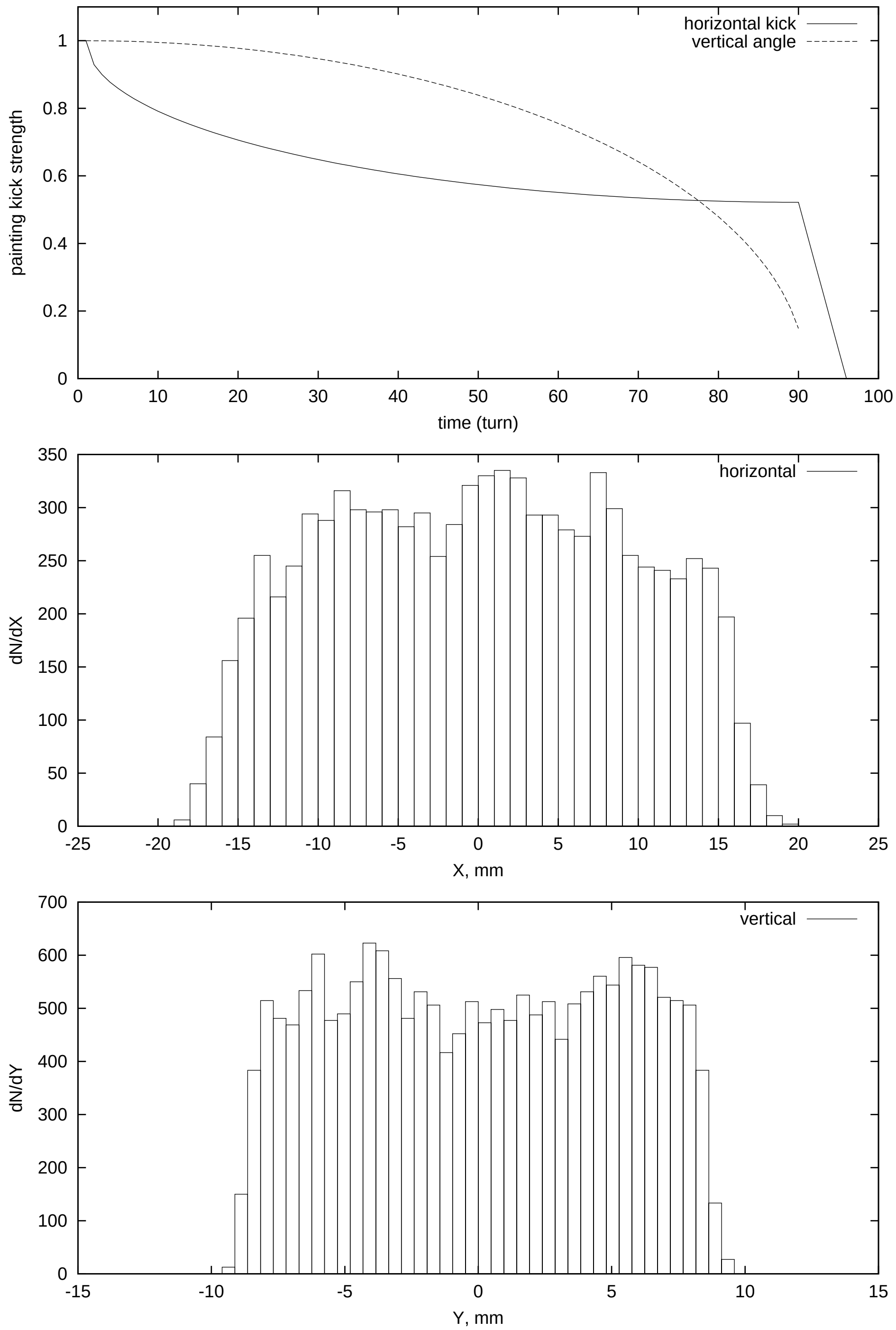


Figure 10: Horizontal kicker strength and vertical angle of the injected beam at the foil (top), circulating beam horizontal (middle) and vertical (bottom) density distribution after injection (96 turn). Graphite foil thickness is $1\ \mu m$. Gaussian distribution of injected beam (with cut to 3 σ). Painting to 11 mm in horizontal plane. Vertical size of injected beam is increased by a factor of 2 (no emittance increase).

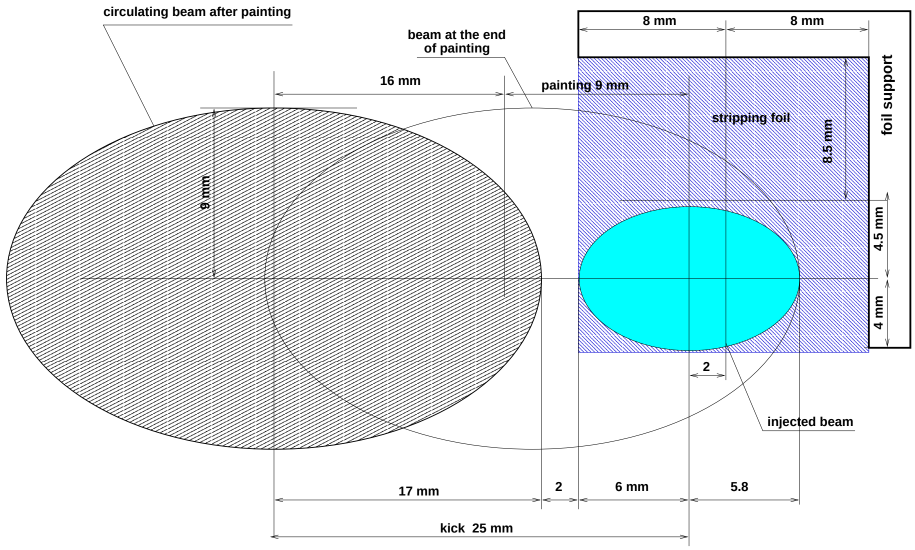


Figure 11: Injected and circulating beam location in the foil at painting. Horizontal and vertical size of injected beam is increased by a factor of 1.5 and 2 (no emittance increase).

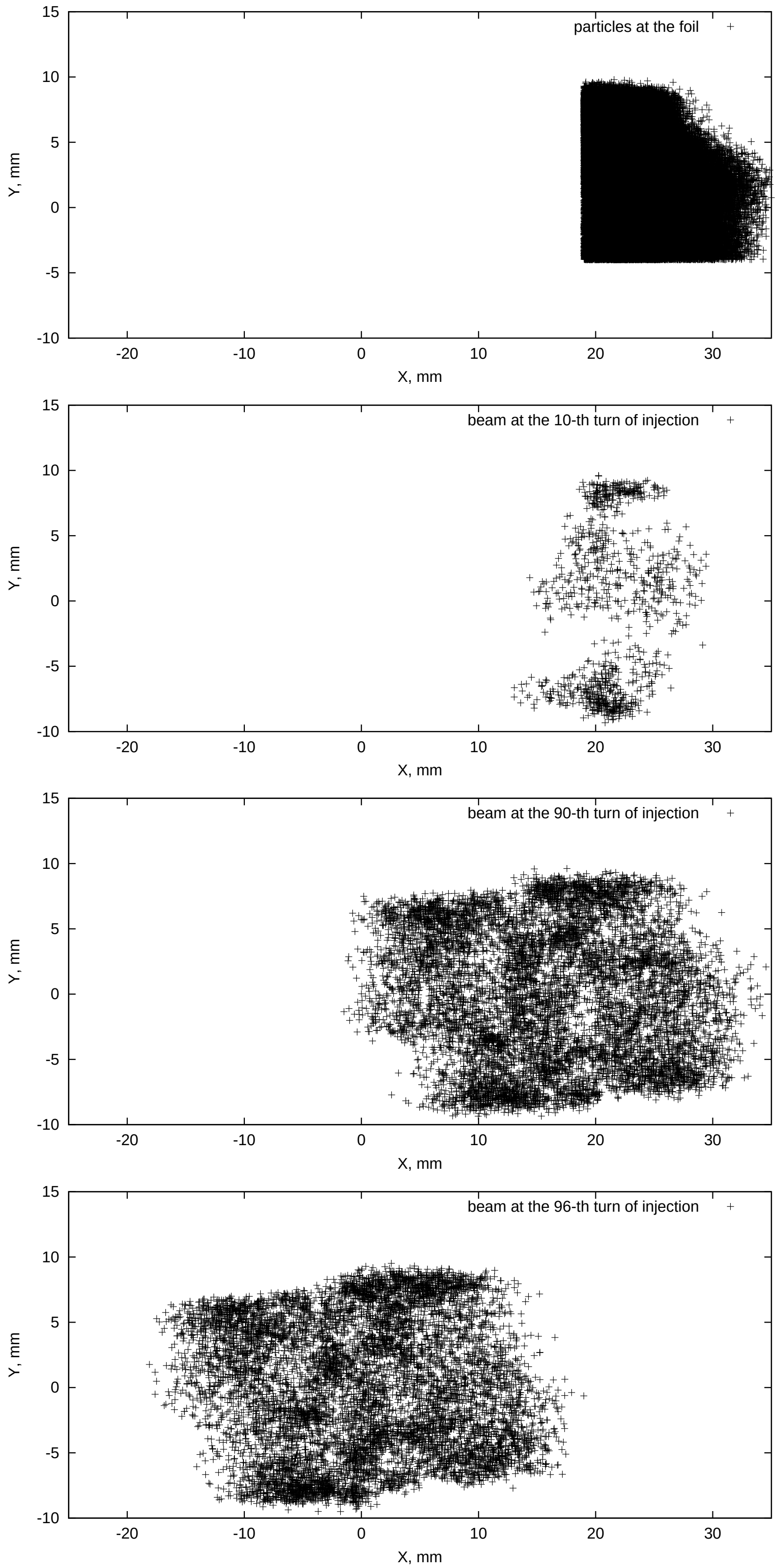


Figure 12: Particles passed through the foil during the total cycle of injection (top), circulating beam after 10 turn of injection (second line), after 90 turn (third line), after beam removal from the foil at 97 turn (bottom). Average number of each particle hits on the foil is 101265/9000=11.25. Betatron tunes are $\nu_x = 26.43, \quad \nu_y = 25.42$. Graphite foil thickness is $1\ \mu m$. Gaussian distribution of injected beam (with cut to 3 σ). Painting to 9 mm in horizontal plane. Size of injected beam is increased by a factor of 1.5 and 2 in horizontal and vertical plane (no emittance increase).

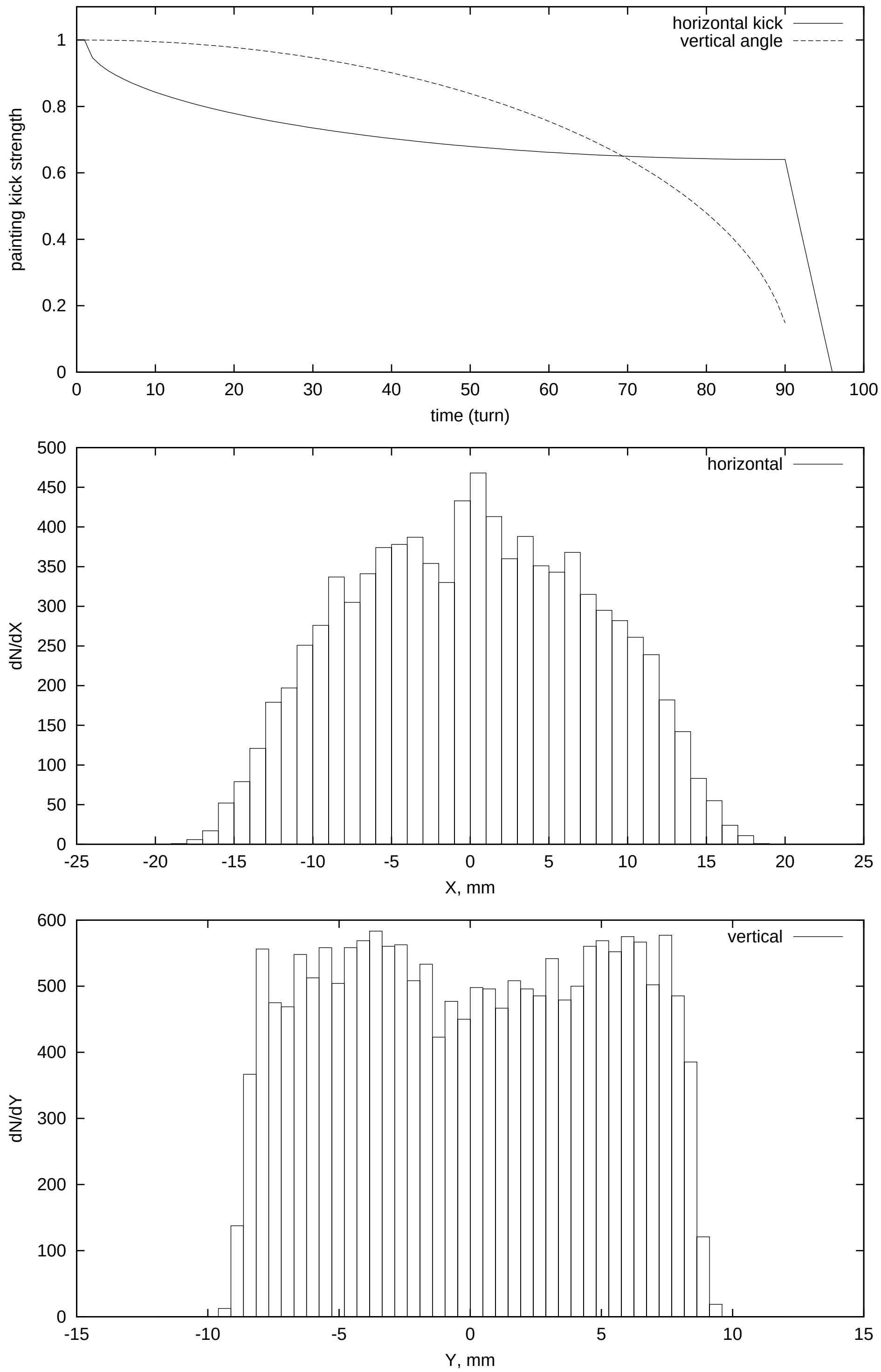


Figure 13: Horizontal kicker strength and vertical angle of the injected beam at the foil (top), circulating beam horizontal (middle) and vertical (bottom) density distribution after injection (96 turn). Graphite foil thickness is $1\ \mu m$. Gaussian distribution of injected beam (with cut to 3 σ). Painting to 9 mm in horizontal plane. Size of injected beam is increased by a factor of 1.5 and 2 in horizontal and vertical plane (no emittance increase).

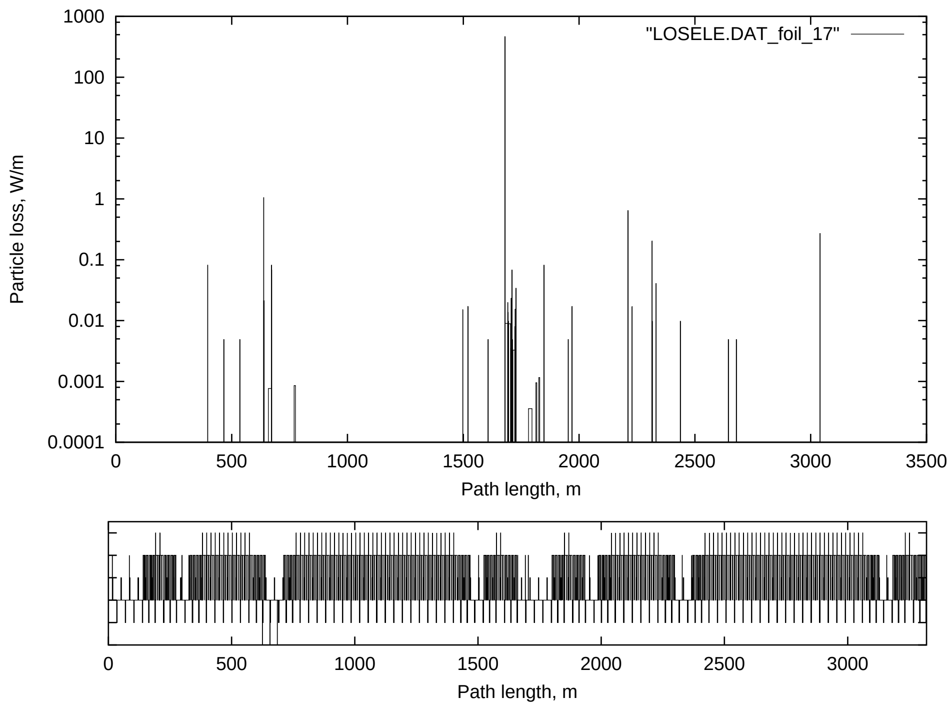


Figure 14: Beam loss distribution at injection with graphite foil thickness of $1\ \mu m$ for 90-turn injection with normal size of injected beam. The rate of particle loss is as low as $7.4 \cdot 10^{-4}$ of injected intensity for 270-turn and a factor of three less for 90-turn injection.